# Dust, Disks, and Planets

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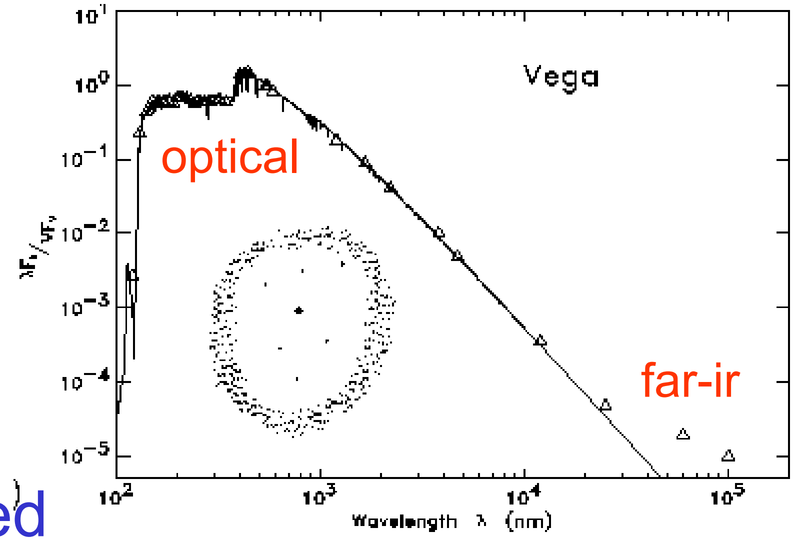
Examples for SAFIR

- Topic 1
  debris disks and planet signatures

- Topic 2
  dust settling in protoplanetary disks

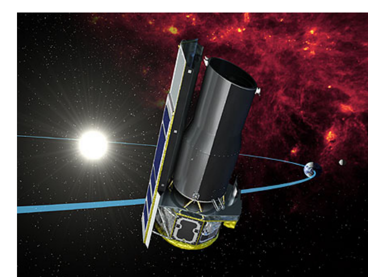
# Debris Disks around Main Sequence Stars

• orbiting dust particles subject to gravity, wind/radiation pressure (ejection) and drag (inspiral)




• $t_{P\text{-}R} = (400/\beta)(M_o/M_*)(r/AU)^2$ yr
<< stellar age (>100 Myr)
dust particles must be replenished

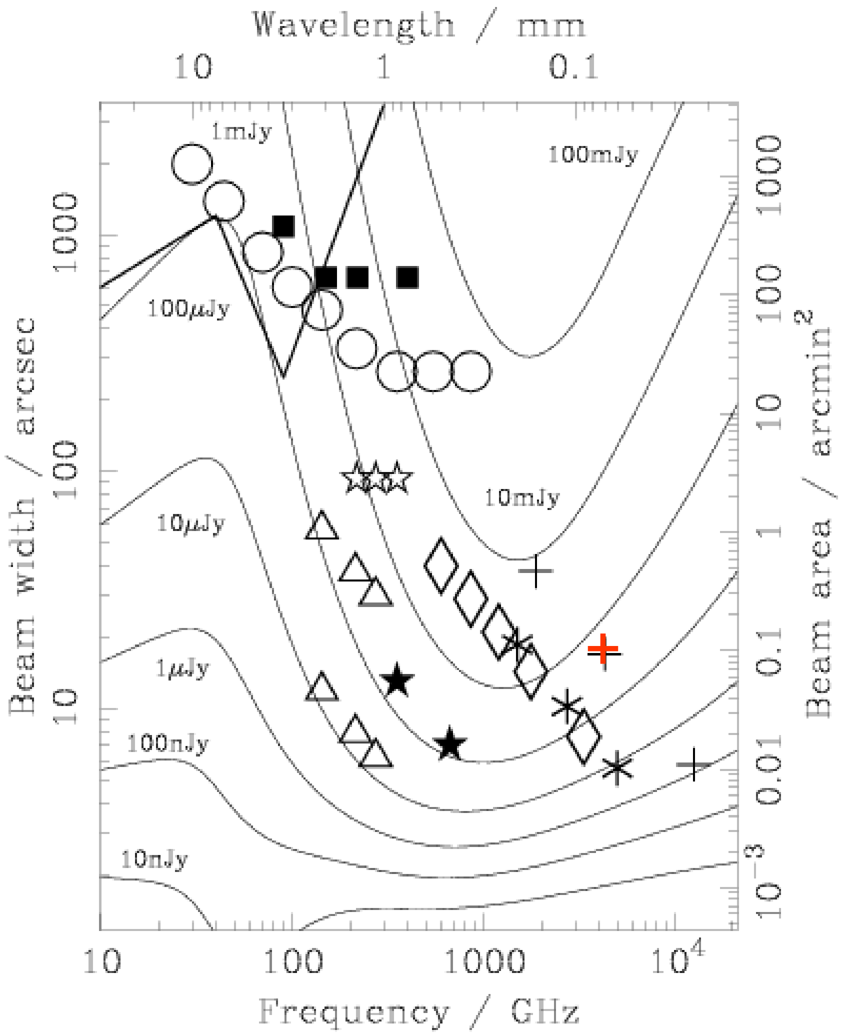
• debris disks are common (>15% of nearby stars), cool (T < 100 K), Kuiper Belt size (R > 50 AU), tenuous ($L/L_* \sim 10^{-5}$ to $10^{-2}$, $M \sim M_{moon}$), gas poor



• Spitzer sensitivity will greatly improve statistics

• periodic perturbations by planets can delay drift, trap dust

# Solar System Analogs and Confusion



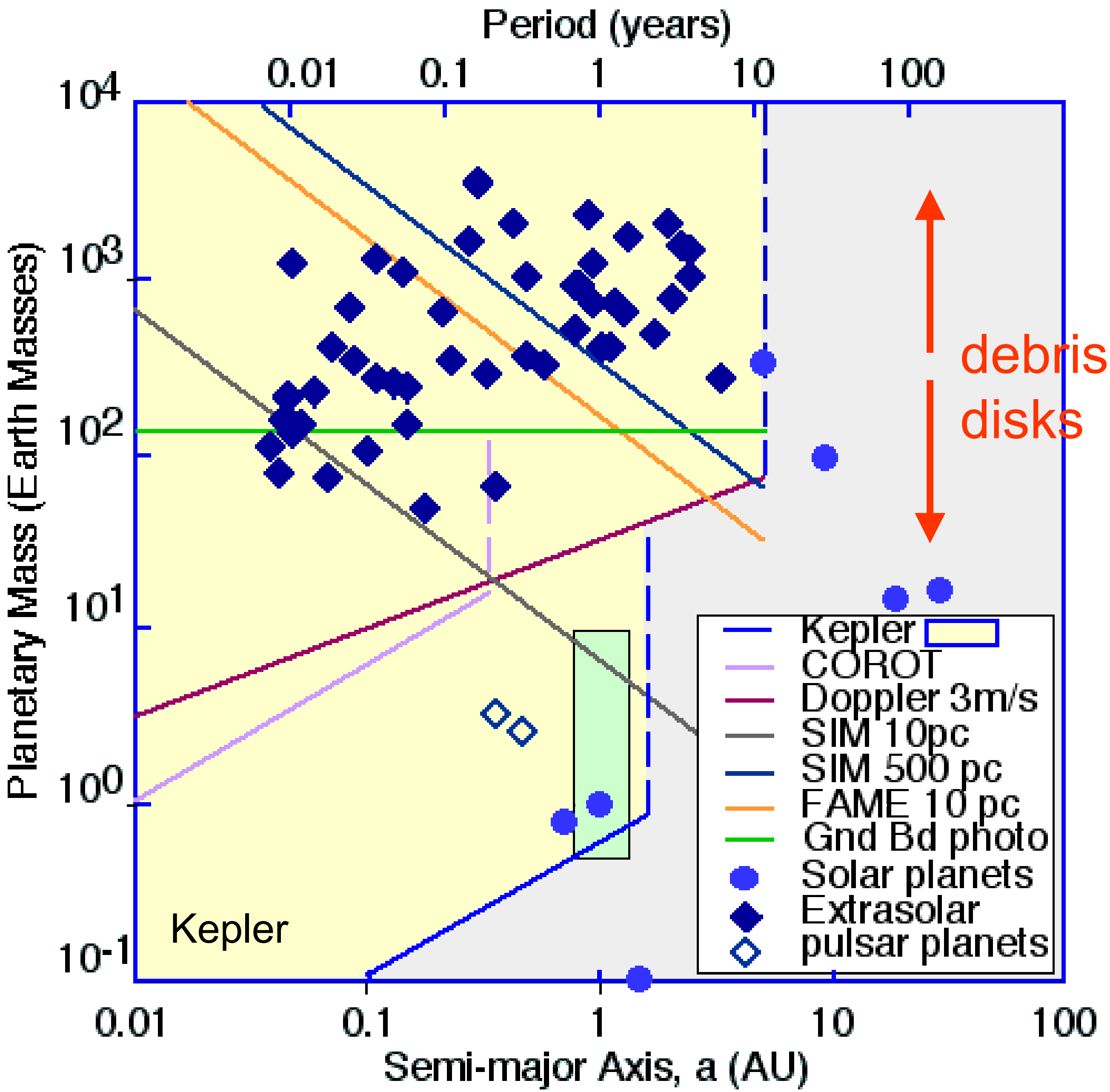

Blain et al. 2002

- Is Solar System unusual?

- Kuiper Belt dust likely $<10^{-5}$ $M_{Earth}$ (Landgraf et al. 2002)
- at 5 pc, size ~10 arcsec
- for Spitzer at 70 $\mu$m, ~125 $\mu$Jy/pix (T~ 40 K), confusion problematic

- ALMA: no confusion, but inadequate sensitivity

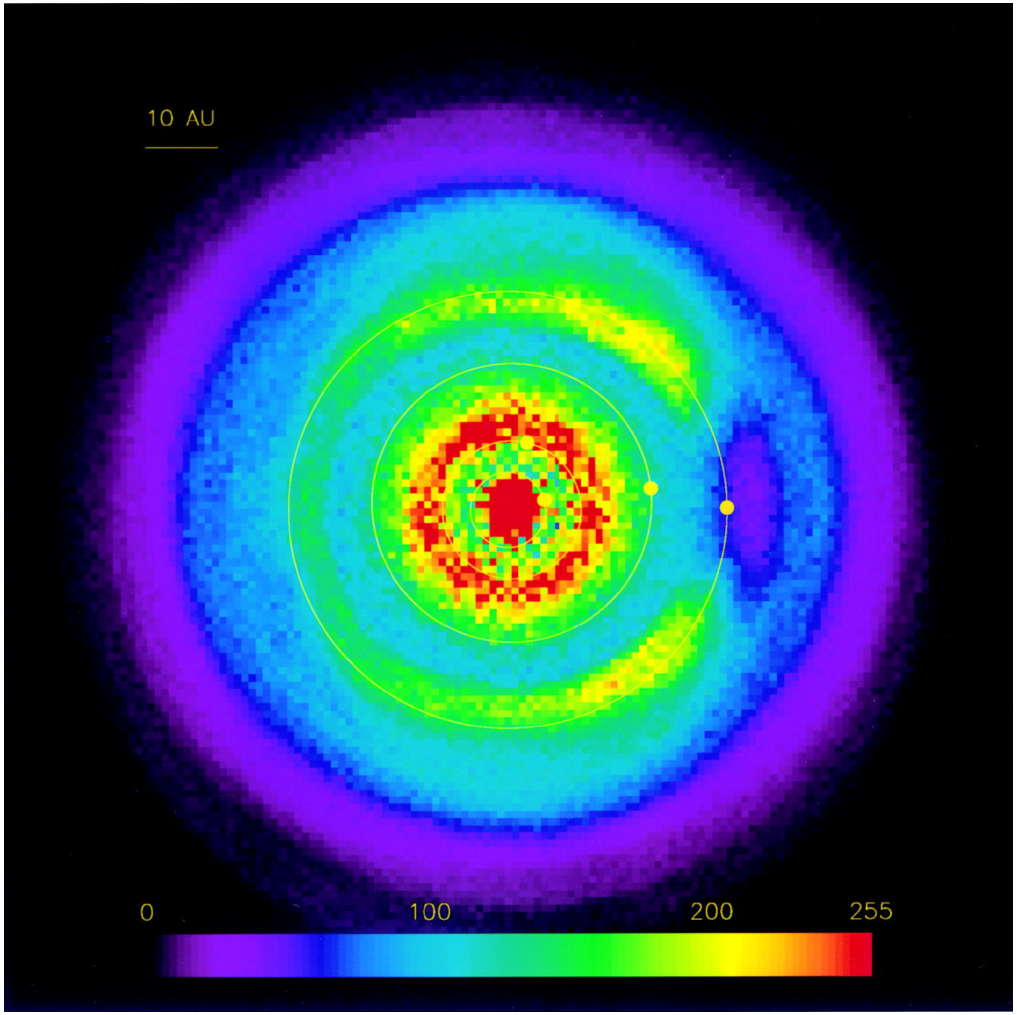
# Planet Parameter Space



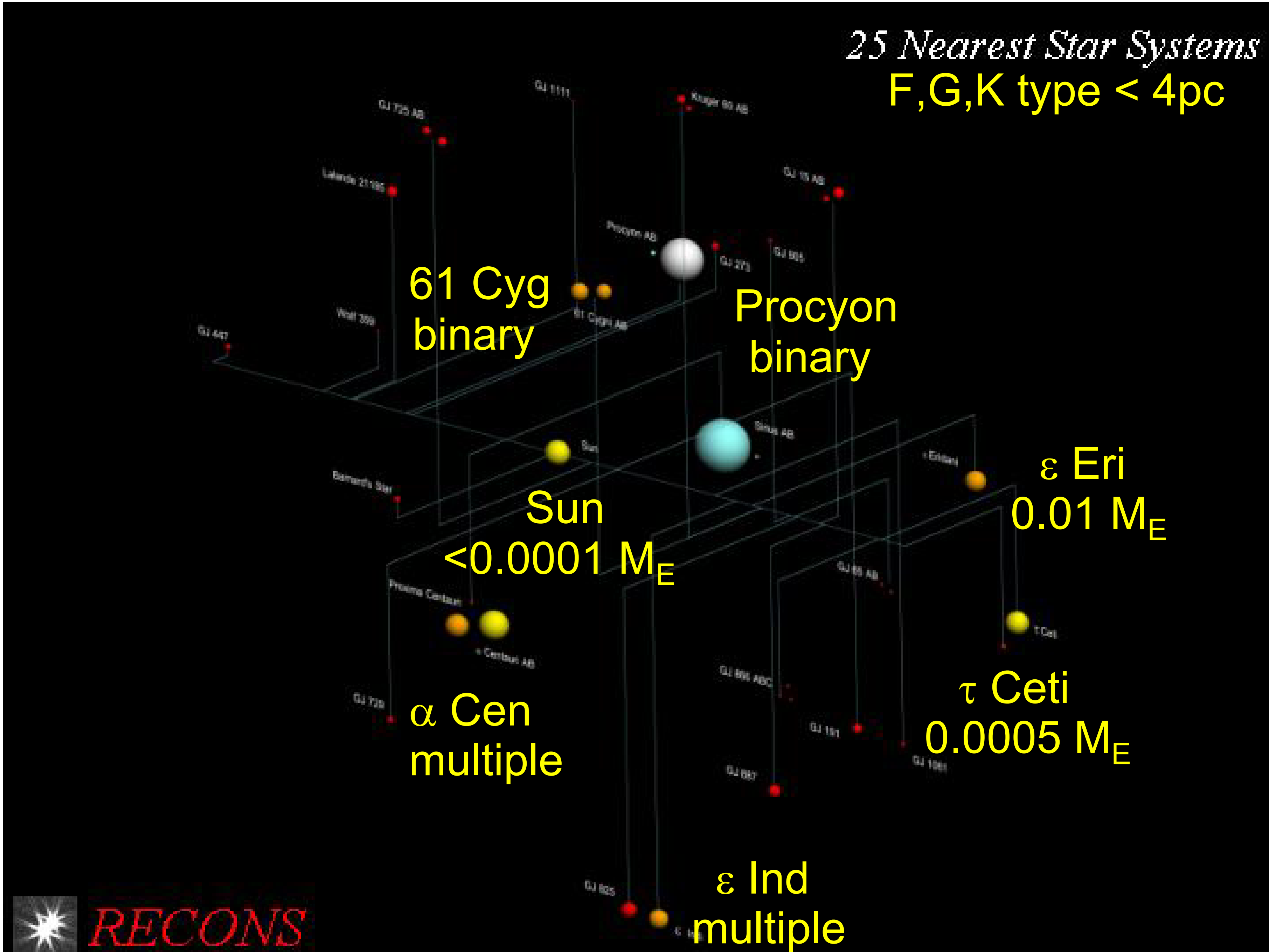
# Dust in our Solar System from Afar

- Liou & Zook (1999) simulations suggest Solar System could be recognized to harbor at least two planets (Neptune, Jupiter)

- constrast depends on $\beta = F_{Rad}/F_{Grav}$ (e.g. Holmes et al. 2003)

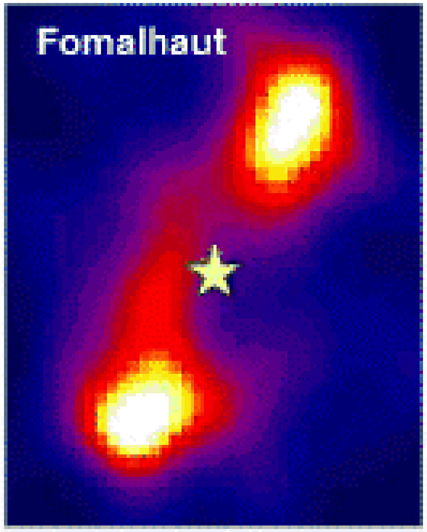


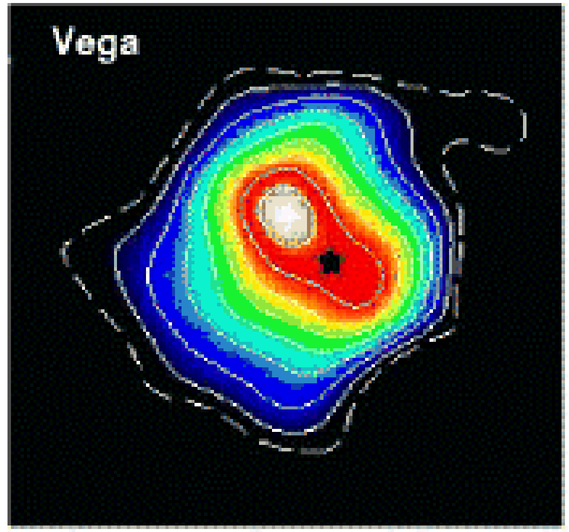

Face-on view of the brightness from a numerical simulation of the emission of 23 μm dust particles from Liou & Zook (1999). The signatures of the planets are (1) deviation from a monotonic radial brightness profile, (2) ring along Neptune orbit, (3) variation along ring, (4) relative lack of particles within 10 AU

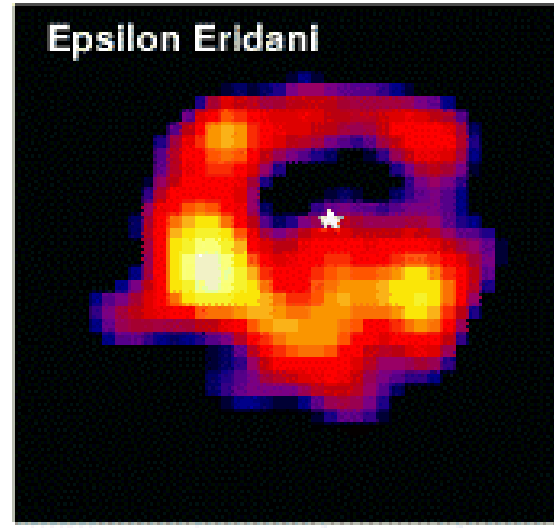


25 Nearest Star Systems
F,G,K type < 4pc
61 Cyg
binary
Procyon
binary
Sun
<0.0001 $M_E$
ε Eri
0.01 $M_E$
α Cen
multiple
τ Ceti
0.0005 $M_E$
ε Ind
multiple
RECONS
GJ 1111
GJ 725 AB
Kruger 60 AB
Lalande 21185
GJ 15 AB
Procyon AB
GJ 273
61 Cygni AB
Wolf 359
GJ 447
Sirius AB
Sun
Barnard's Star
Proxima Centauri
GJ 65 AB
GJ 866 ABC
GJ 729
GJ 191
GJ 1061
GJ 887
GJ 825

# Resolved Debris Disks




- Submm images: disk-like rings w/holes, arcs, clumps, blobs (Holland et al. 1998, 2003; Greaves et al. 1998)
- two flavors of dust-planet models (Wilner et al. 2002):

  - outer belt of planetesimals and dust produce non-resonant particles that inspiral and become trapped in resonances

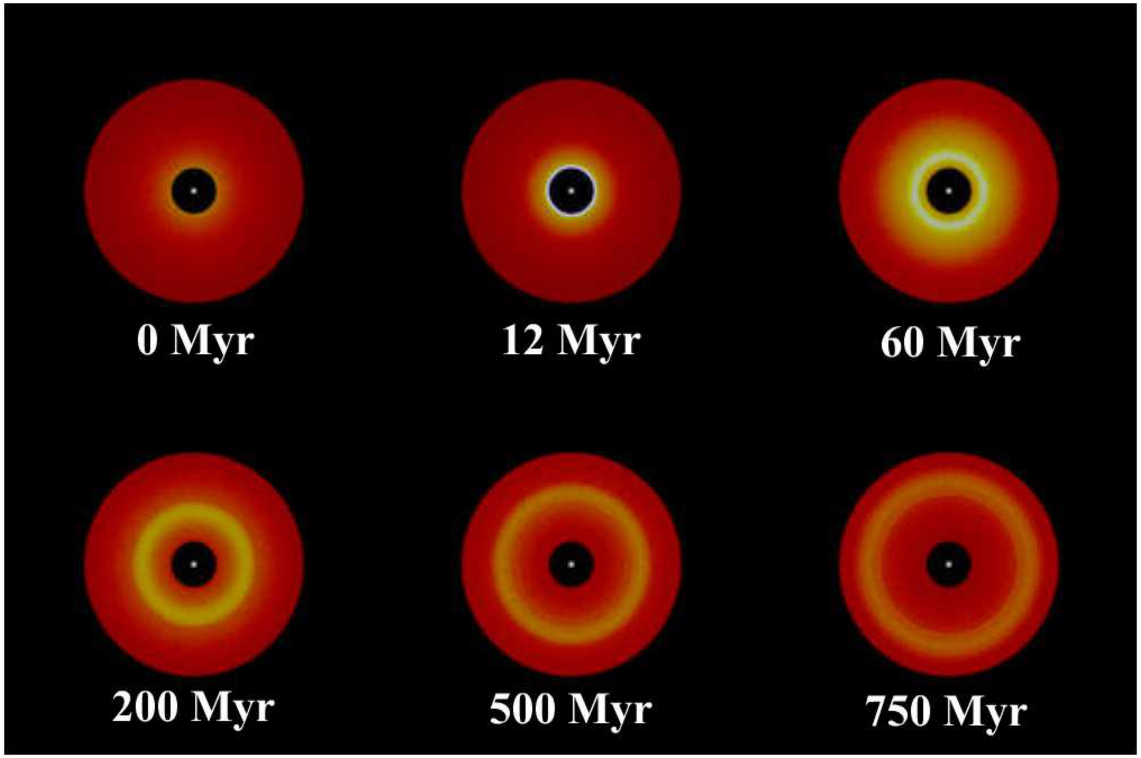
  - parent bodies of dust trapped in resonances (like Plutinos)

# Rings are Signposts of Planet Stirring?

- bright ($L \sim 10^{-4}\ L_*$) narrow ($\Delta a/a \sim 0.1$) rings of observed scales explained by collisional cascade in planetesimal disk stirred by (recent) formation of bodies of radius >1000 km

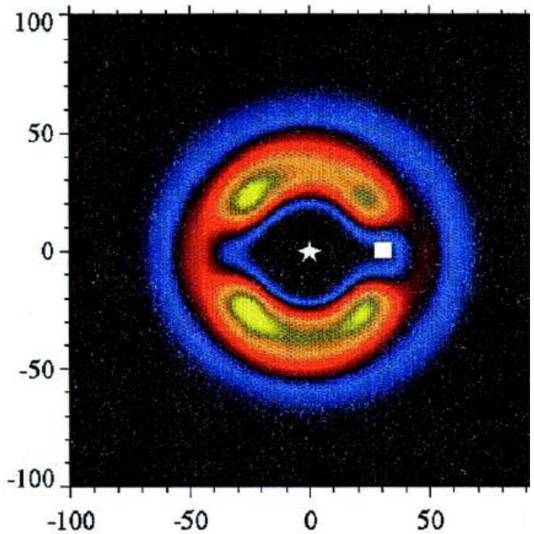
- does not account for azimuthal variations

(Kenyon & Bromley 2002, 2004)

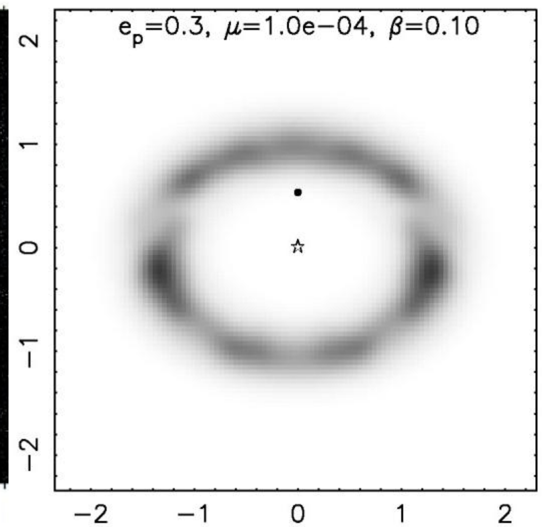


# ε Eridani: Sculpting by a Planet?

0.2 $M_{Jup}$
e = 0
2:1, 3:2
w/ high
libration




Ozernoy et al. 2000

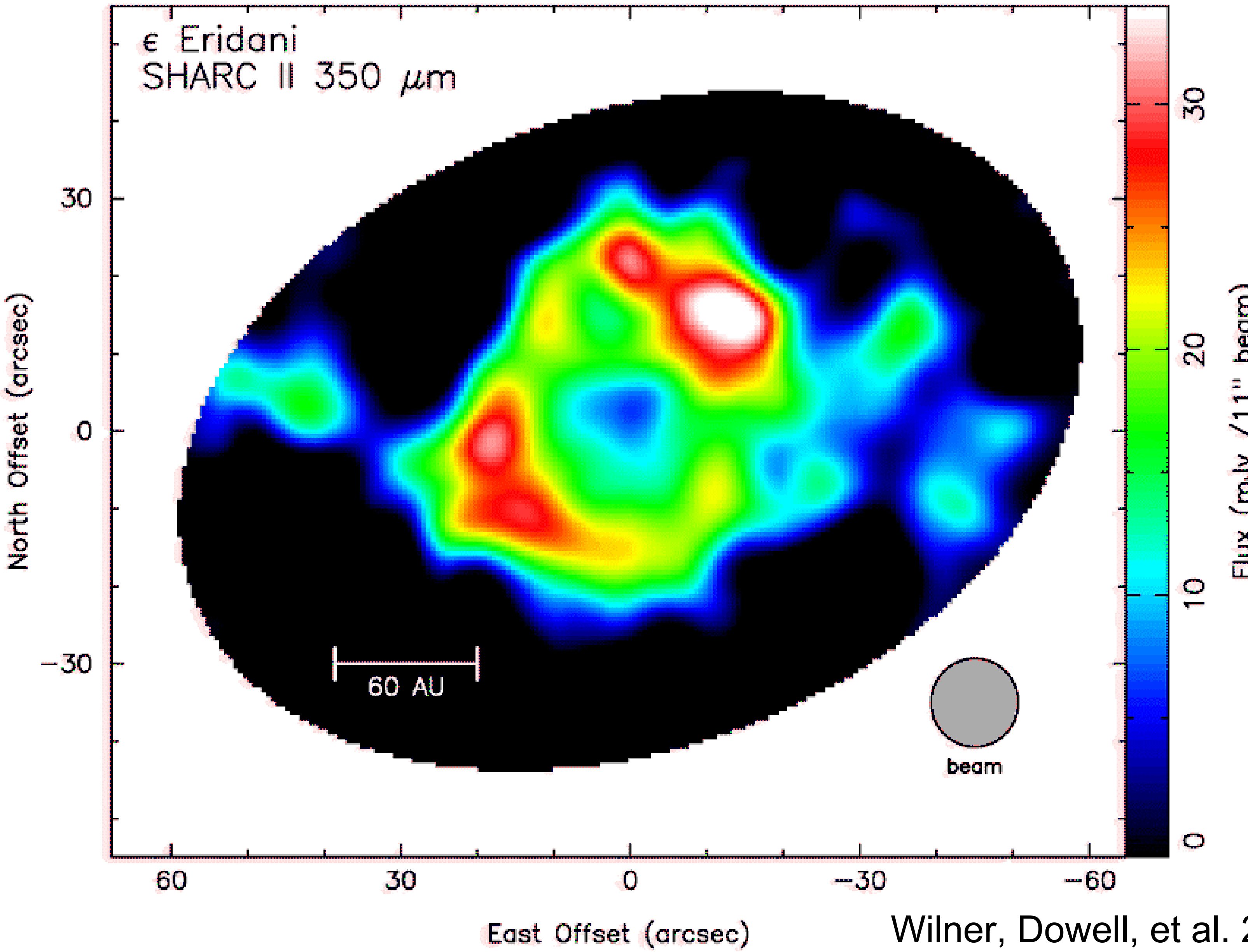



Quillen & Thorndike 2002

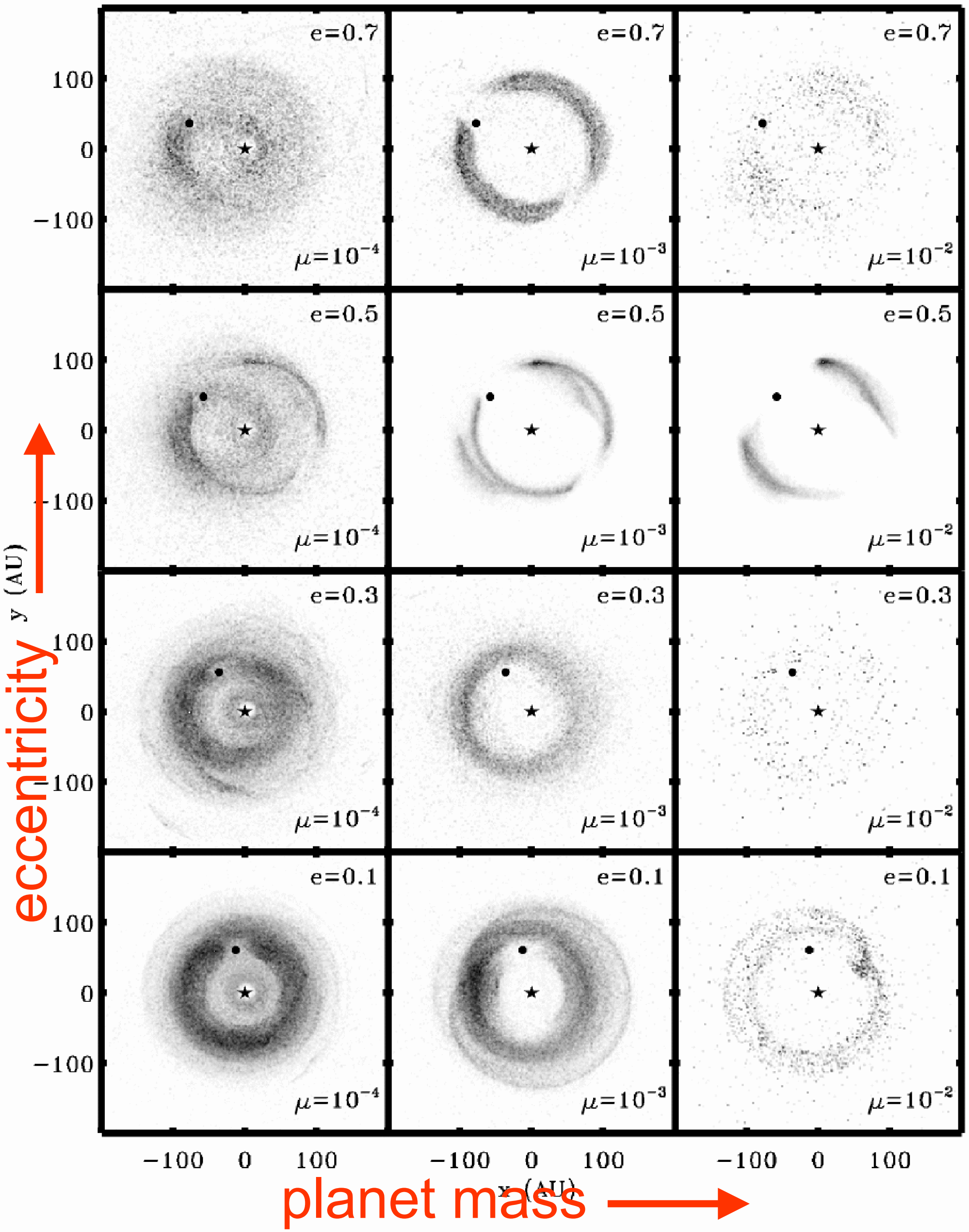
< 0.3 $M_{Jup}$
e ~ 0.3
5:3, 3:2
w/ phase
segregation

- models that selectively populate resonances are not realistic unless motivated by e.g. parent bodies trapped by planet migration (Vega? See Wyatt 2003), encounter, ...
- models predict time dependence that can be tested

# ε Eridani: new 350 μm CSO Observations




Wilner, Dowell, et al. 2004



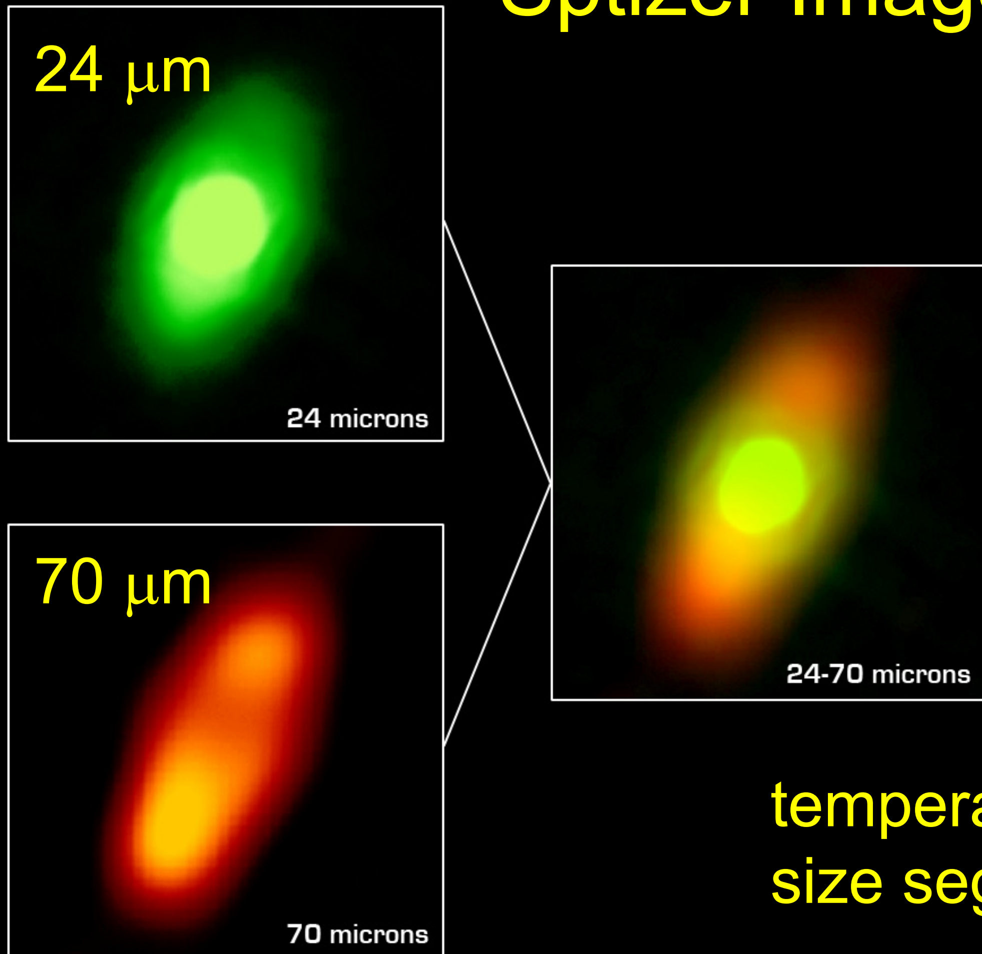

# Modeling Directions

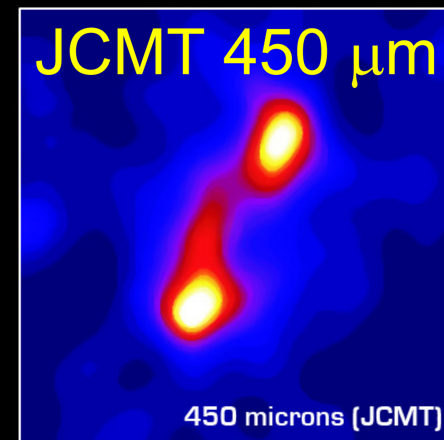
- planet parameters (mass, eccentricity, semi-major axis, inclination, ...)
- initial conditions of dust parent bodies

- collisional systems where $t_{coll} << t_{MMR}$
- particle size range ($\beta$ small and large)

Kuchner & Holman

# Sptizer Images of Fomalhaut




temperature +
size segregation?

Fomalhaut Circumstellar Disk

Spitzer Space Telescope • MIPS

NASA / JPL-Caltech / K. Stapelfeldt (JPL)

ssc2003-06i

# Stages of Disk Evolution/Planet Formation

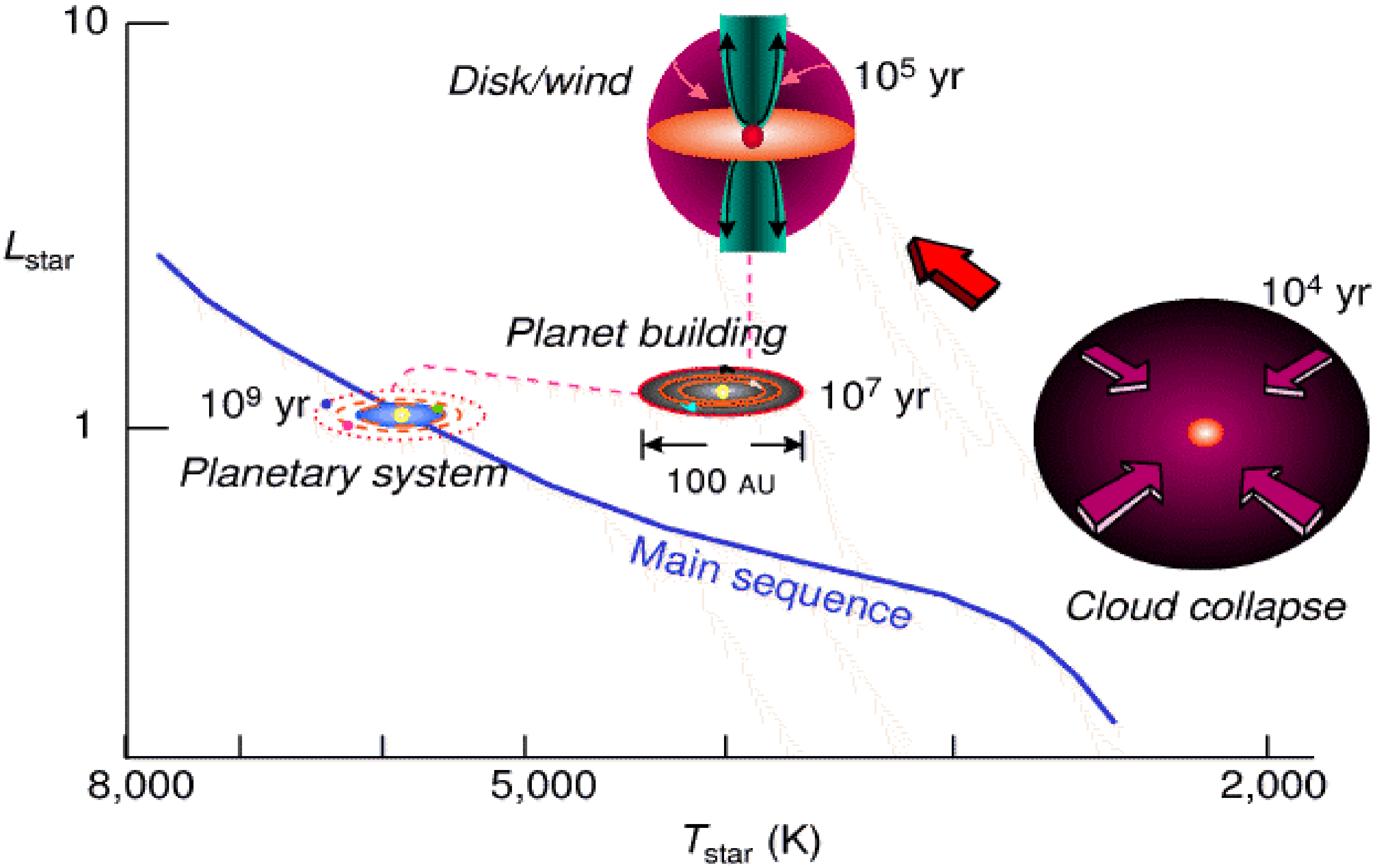
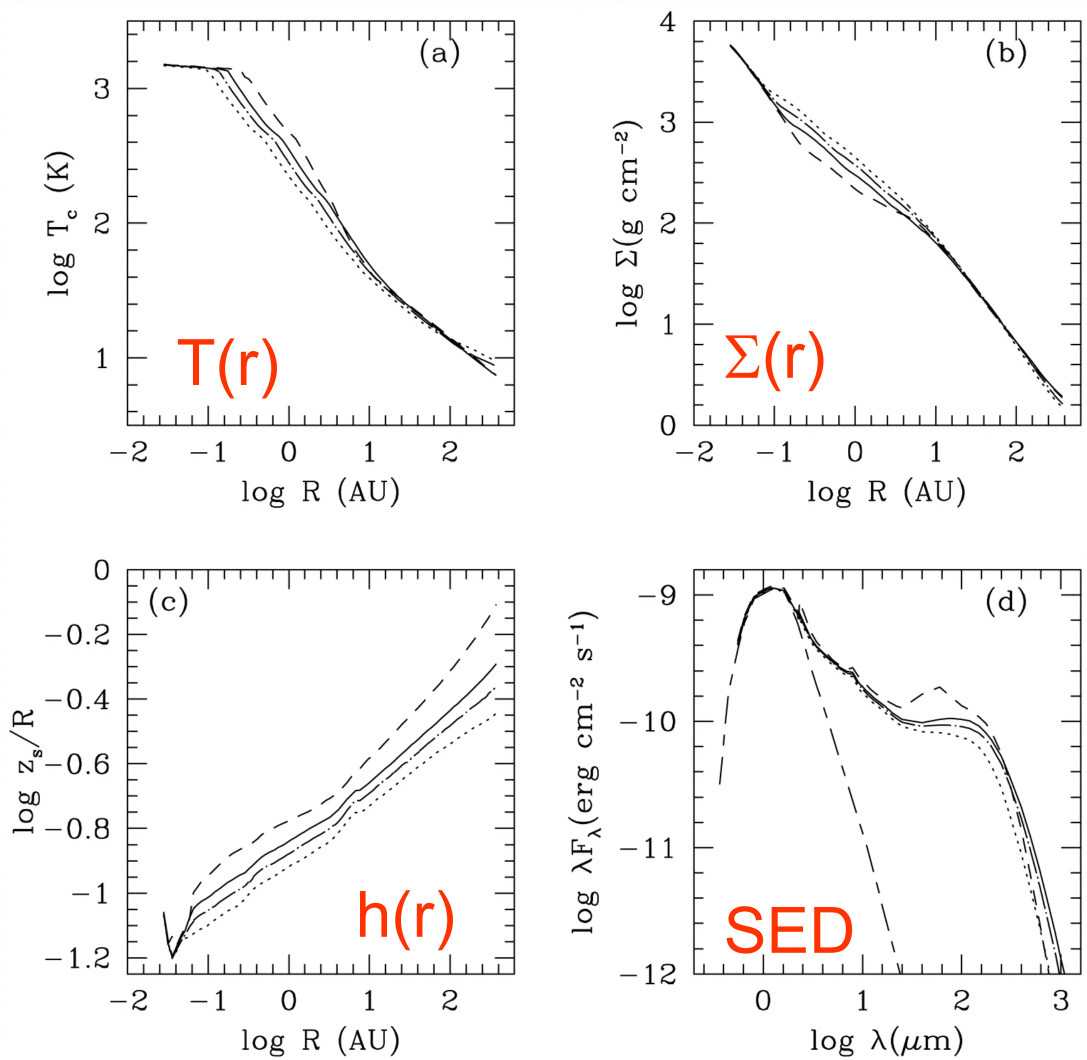


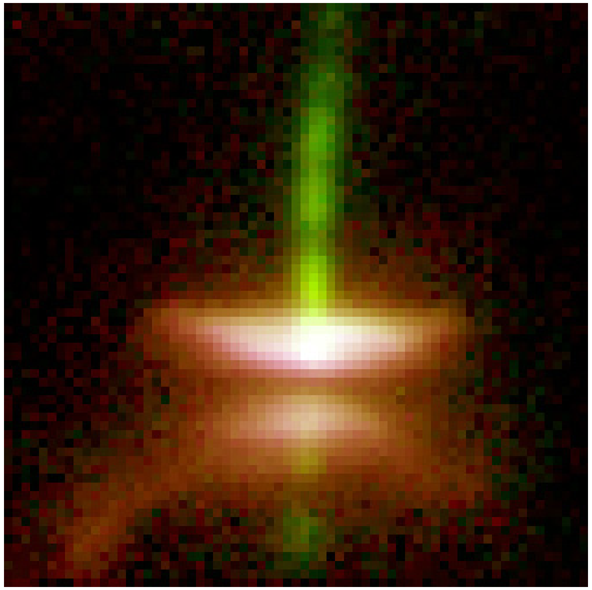

Fig. 2, Beckwith & Sargent, *Nature*, **383**, 139-144.

# Protoplanetary Disks are Multi-λ Objects



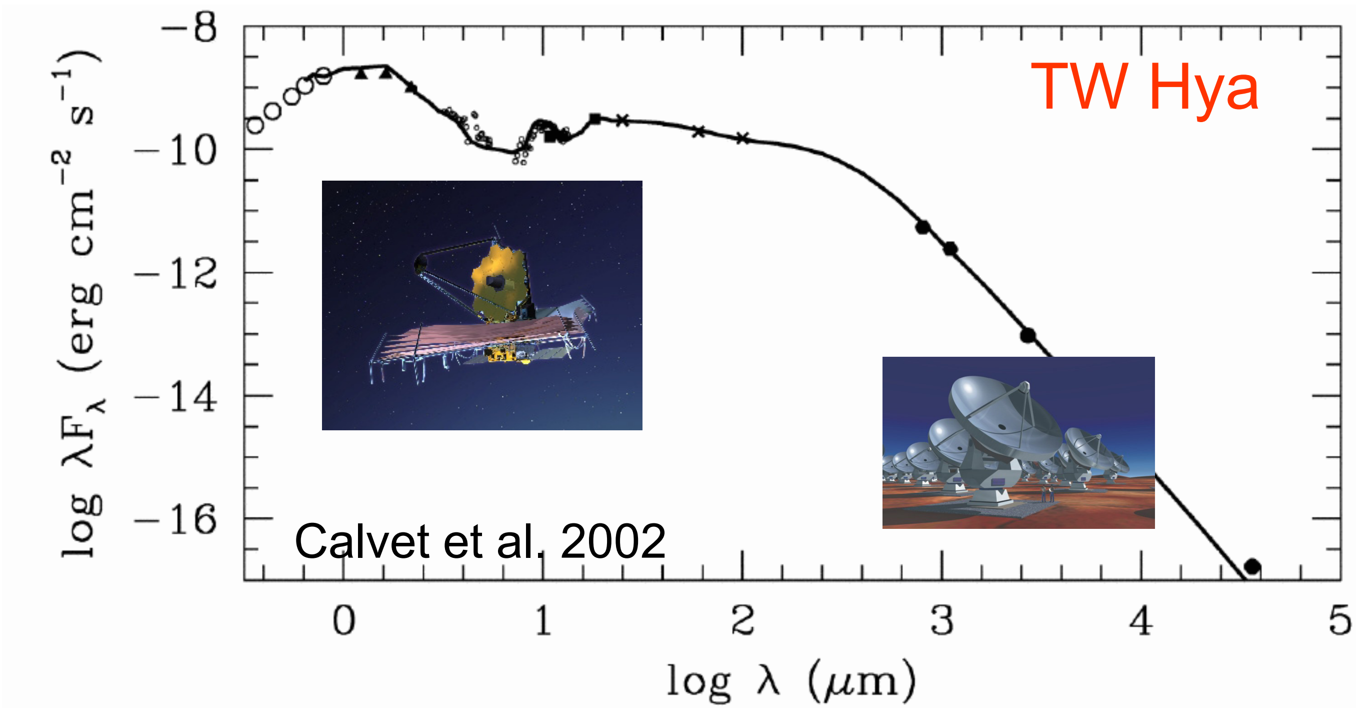

D'Alessio et al. 2001

gas and dust with radial and vertical gradients (n,T, ...)

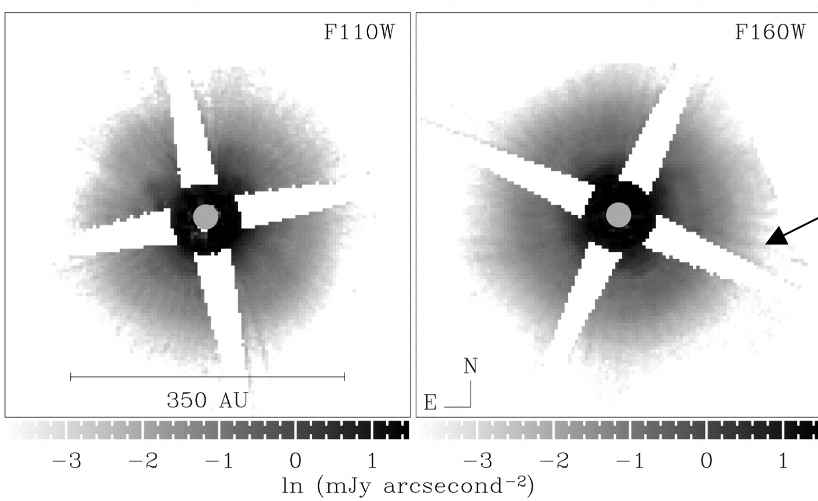


surface shape

irradiation



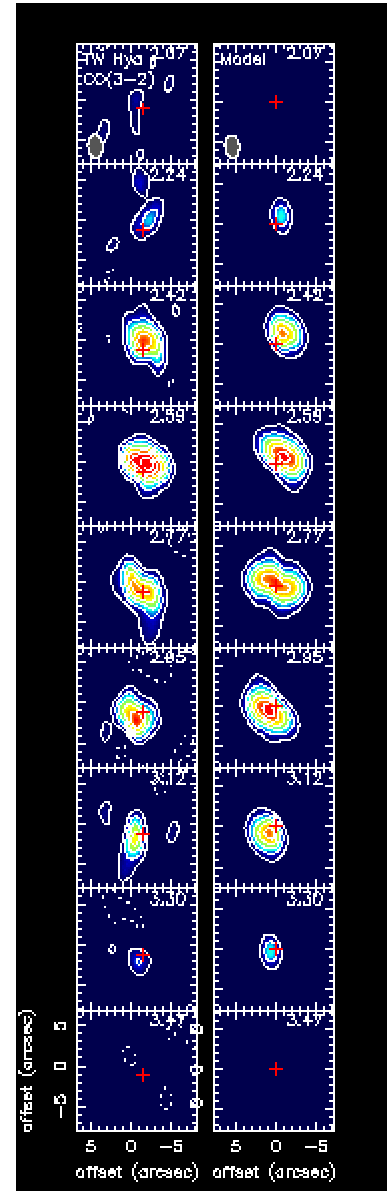

Calvet et al. 2002




Weinberger et al. 2002

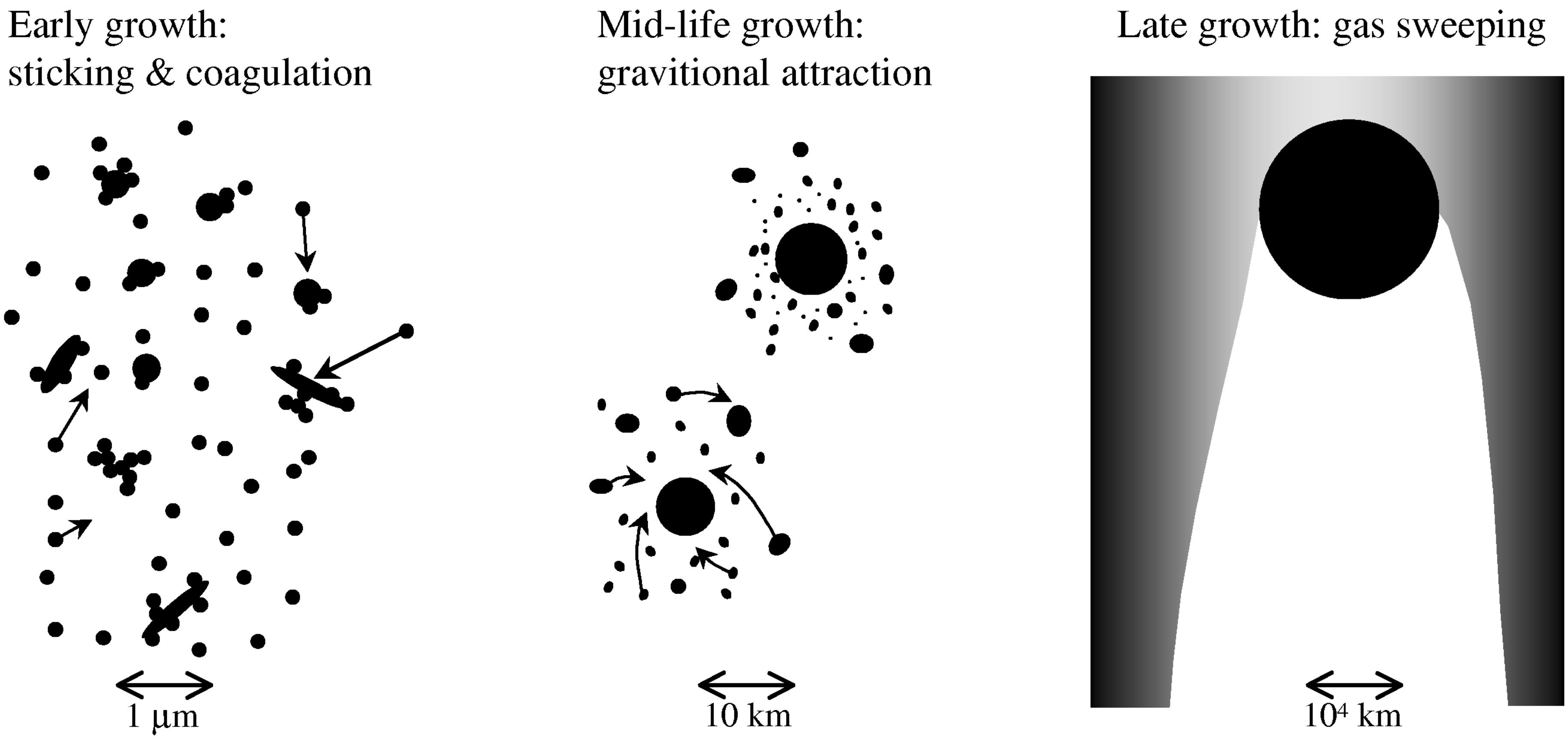
scattered light:
HST/NICMOS
(JWST)

submm CO:
SMA
(ALMA)




Qi et al. 2004

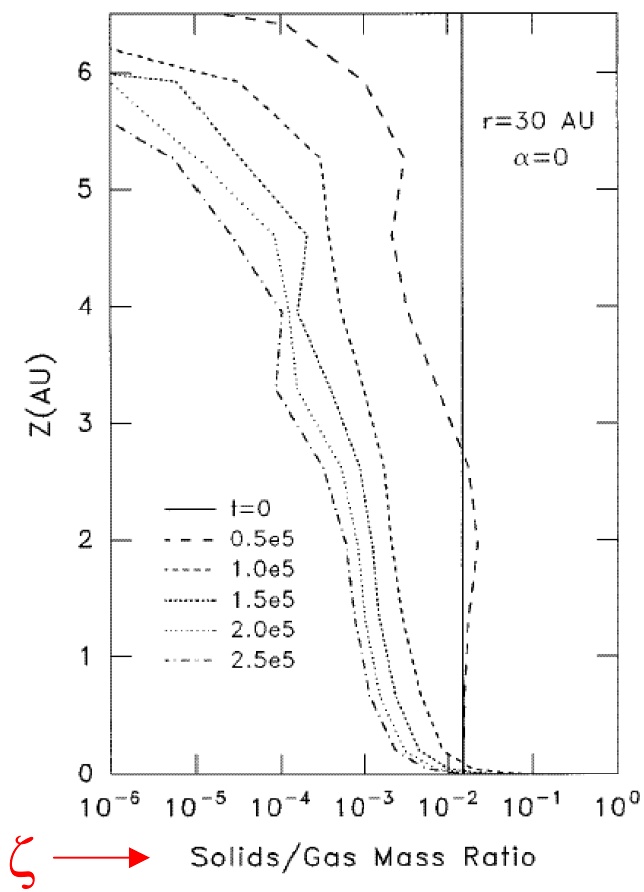
# Grain Growth to Planetismals and Planets




Beckwith et al. 2000

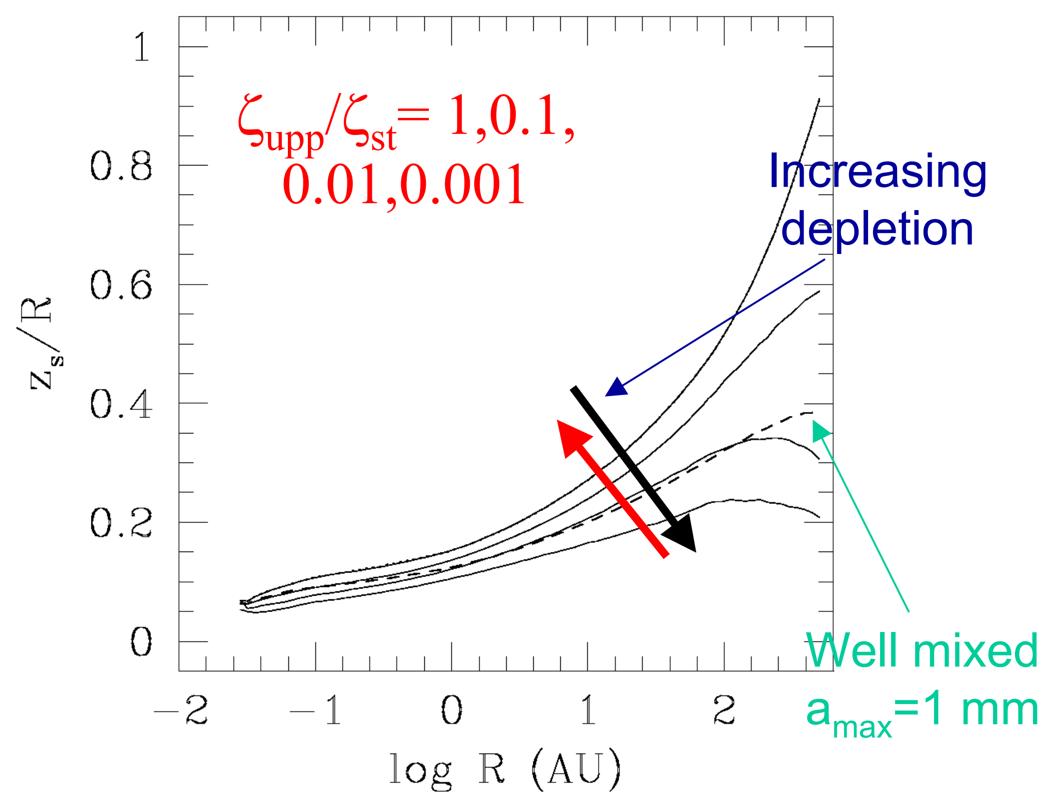
# Settling – Dust Evolution in Solar Nebula

Decrease of dust/gas in upper layers




Weidenschilling 1997

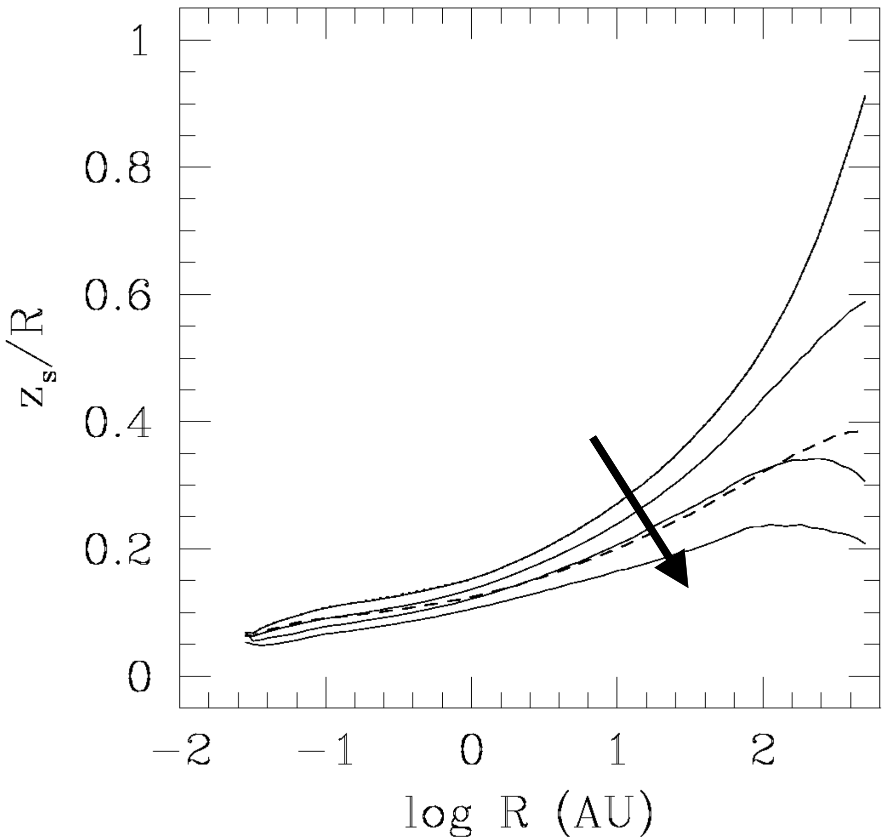
Lower surface (even with small grains in upper layers)



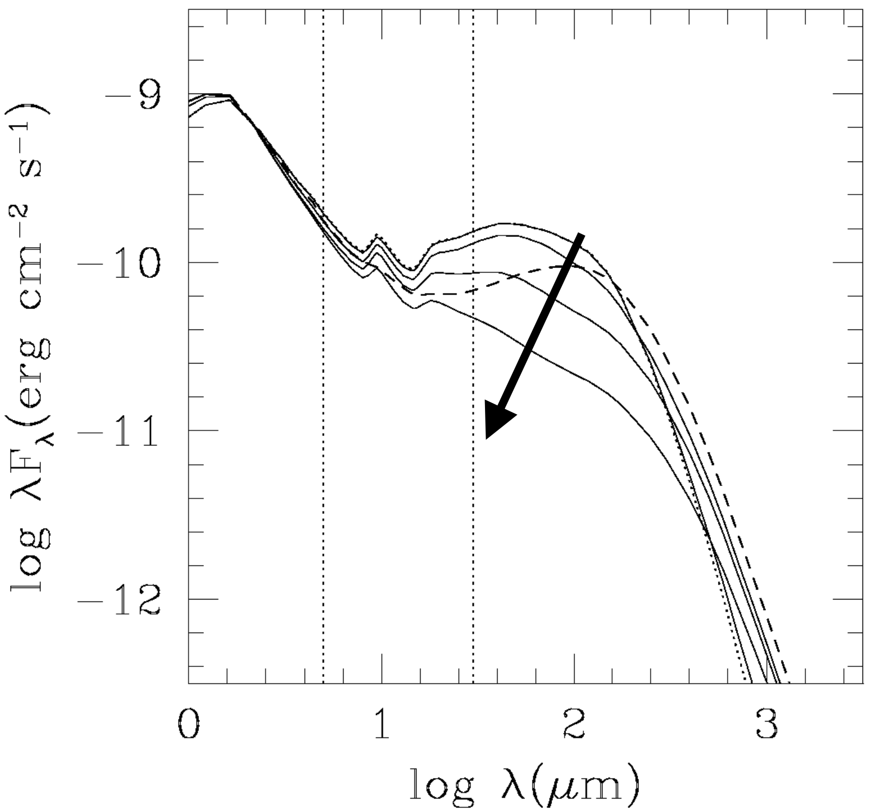

D'Alessio 2004

# Dust Settling Modifies Disk Shape/Spectrum

$\zeta_{upp}/\zeta_{st}$= 1,0.1, 0.01,0.001

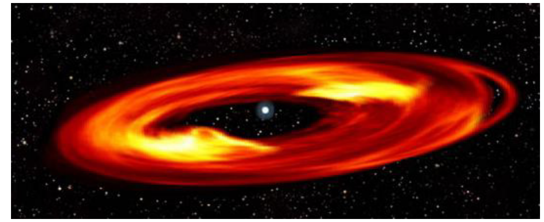



Lower FIR and silicate emission




D'Alessio et al. 2004

# Summary



- Far-Infrared is key spectral regime for dusty disks.

- Large apertures needed to beat confusion for true analogs of Solar System dust. Sensitivity/resolution/calibration are all important!

- Inference of unseen planets from debris disk structure is promising (and most interesting for large separations). High confidence requires better images, far-infrared to mm, and more sophisticated modeling.

- Many applications to protoplanetary disk evolution, e.g. dust coagulation and settling to midplane